

## **Title: Upper Ocean Structure: Wind and Buoyancy-forced Upper Ocean**

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### **I. Introduction**

Forcing from winds, heating and cooling, and rainfall and evaporation, have a profound influence on the distribution of mass and momentum in the ocean. While the effects from this wind and buoyancy forcing are ultimately felt throughout the entire ocean, the most immediate impact is in the surface mixed layer, the site of the active air-sea exchanges. The mixed layer is warmed by sunshine and cooled by radiation emitted from the surface and by latent heat loss due to evaporation (Figure 1). The mixed layer also tends to be cooled by sensible heat loss since the surface air temperature is generally cooler than the ocean surface. Evaporation and precipitation change the mixed layer salinity. These salinity and temperature changes define the ocean's surface buoyancy. As the surface loses buoyancy, the surface can become denser than the subsurface waters, causing convective overturning and mixing to occur. Wind mixing is another source of surface turbulence. Surface turbulence causes the surface water to be well-mixed and vertically uniform in temperature, salinity and density. Furthermore, the turbulence can entrain deeper waters into the surface mixed layer, causing the surface temperature and salinity to change and the layer of well-mixed, vertically uniform water to thicken. Wind forcing can also set up oceanic currents and cause changes in the mixed layer temperature and salinity through horizontal and vertical advection.

Although the ocean is forced by the atmosphere, the atmosphere can also respond to

ocean surface conditions, particularly sea surface temperature (SST). Direct thermal circulation, in which moist air rises over warm SSTs and descend over cool SSTs, is most prevalent in the tropics. The resulting atmospheric circulation cells influence the patterns of cloud, rain, and winds that combine to form the wind and buoyancy forcing for the ocean. Thus, the oceans and atmosphere form a coupled system, where sometimes it is difficult to distinguish forcing from response. Because water has a heat capacity and density nearly three orders of magnitude larger than air, the ocean has thermal and mechanical inertia relative to the atmosphere. The ocean thus acts as a memory for the coupled ocean-atmosphere system.

We begin with a discussion of air-sea interaction through surface heat fluxes, moisture fluxes, and wind forcing. The primary external force driving the ocean-atmosphere system is radiative warming from the sun. Because of the fundamental importance of solar radiation, we illustrate surface wind and buoyancy forcing with two examples of the seasonal cycle. The first case describes the seasonal cycle in the north Pacific, and can be considered a classic example of a one-dimensional (involving only vertical processes) ocean response to wind and buoyancy forcing. In the second example, the seasonal cycle of the eastern tropical Pacific, the atmosphere and ocean are coupled, so that wind and buoyancy forcing lead to a sequence of events that make cause and effect difficult to determine. The impact of wind and buoyancy forcing on the surface mixed layer and the deeper ocean is summarized in the conclusion.

## **II. Air-sea interaction**

### ***A. Surface heat flux***

As shown in Figure 1, the net surface heat flux entering the ocean ( $Q_0$ ) includes solar

radiation ( $Q_{sw}$ ), net longwave radiation ( $Q_{lw}$ ), latent heat flux due to evaporation ( $Q_{lat}$ ), and sensible heat flux due to air and water having different surface temperatures ( $Q_{sen}$ ):

$$Q_0 = Q_{sw} + Q_{lw} + Q_{lat} + Q_{sen}$$

The Earth's seasons are largely defined by the annual cycle in the net surface heat flux associated with the astronomical orientation of the Earth relative to the Sun. The Earth's tilt causes solar radiation to strike the winter hemisphere more obliquely than the summer hemisphere. As the Earth orbits the sun, winter shifts to summer and summer shifts to winter, with the sun directly overhead at the equator twice per year, in March and again in September. Thus, one might expect the seasonal cycle in the tropics to be semi-annual, rather than annual. However, as discussed in Section III, in some parts of the equatorial oceans, the annual cycle dominates due to coupled ocean-atmosphere-land interactions.

Solar radiation entering the Earth's atmosphere is absorbed, scattered, and reflected by water both in its liquid and vapor forms. Consequently, the amount of solar radiation which crosses the ocean surface,  $Q_{sw}$ , also depends upon the cloud structures. The amount of solar radiation absorbed by the ocean mixed layer depends upon the transmission properties of the light in the water and can be estimated as the difference between the solar radiation entering the surface and the solar radiation penetrating through the base of the mixed layer (i.e.,  $Q_{sw} - Q_{pen}$  in Figure 1).

The Earth's surface also radiates energy at longer wavelengths similar to a blackbody (i.e. proportional to the fourth power of the surface temperature in units Kelvin). Longwave radiation emitted from the ocean surface can reflect against clouds and become downwelling longwave radiation to be reabsorbed by the ocean. Thus net longwave radiation,  $Q_{lw}$ , is the combination of

the outgoing and incoming longwave radiation and tends to cool the ocean.

The ocean and atmosphere also exchange heat via conduction (“sensible” heat flux).

When the ocean and atmosphere have different surface temperatures, sensible heat flux will act to reduce the temperature gradient. Thus when the ocean is warmer than the air (which is nearly always the case), sensible heat flux will tend to cool the ocean and warm the atmosphere.

Likewise, the vapor pressure at the air-sea interface is saturated with water while the air just above the interface typically has relative humidity less than 100%. Thus, moisture tends to evaporate from the ocean and in doing so, the ocean loses heat. This moisture can condense in the atmosphere to form clouds, releasing heat to the atmosphere and affecting the large-scale wind patterns.

Because sensible and latent heat loss are turbulent processes, they also depend upon wind speed relative to the ocean surface. Using similarity arguments, one can express the latent ( $Q_{lat}$ ) and sensible ( $Q_{sen}$ ) heat fluxes in terms of “bulk” properties at and near the ocean surface:

$$Q_{lat} = \rho_a L C_E S (q_a - q_s)$$

$$Q_{sen} = \rho_a C_H S (T_a - T_s)$$

where  $\rho_a$  is the air density,  $L$  is the latent heat of evaporation,  $C_E$  and  $C_H$  are the transfer coefficient of latent and sensible heat flux,  $S$  is the surface wind speed relative to the ocean surface,  $q_s$  is the saturated specific humidity at the sea surface temperature,  $T_s$ , and  $q_a$  and  $T_a$  are respectively the specific humidity and temperature of the air at a few meters above the air-sea interface. The units of the heat fluxes are  $W m^{-2}$  and a positive flux will tend to heat the ocean surface. The transfer coefficients,  $C_E$  and  $C_H$ , depend upon the wind speed and stability properties of the atmospheric boundary layer, making estimations of the heat fluxes quite difficult. Most

algorithms estimate the turbulent heat fluxes iteratively, using first estimates of the heat fluxes to compute the transfer coefficients. Further, the dependence of heat flux on wind speed and SST causes the system to be coupled since the heat fluxes can change the wind speed and SST.

Fig. 2 shows the climatological net surface heat flux,  $Q_0$ , and SST for the entire globe. Several patterns are evident. In general, the tropics are heated more than the poles causing warmer SST in the tropics and cooler SST at the poles. Also, there are significant zonal asymmetries in both the net surface heat flux and SST. The largest heat losses occur over the western boundary currents where SST is high and winds are strong (causing large latent and sensible heat losses). Often the seasonal conditions are quite different than mean climatology. In Section III, we discuss the seasonal warming and cooling in the north Pacific and the eastern equatorial Pacific.

### ***B. Thermal and haline buoyancy fluxes***

Since the density of seawater depends upon temperature and salinity, air-sea heat and moisture fluxes can change the surface density making the water column more or less buoyant. Specifically, surface heat flux ( $Q_0$ ), rate of evaporation ( $E$ ) and precipitation ( $P$ ) can be expressed as a buoyancy flux ( $B_0$ ), as:

$$B_0 = -g \alpha Q_0 / (\rho c_p) + g \beta (E - P) S_0 \quad (1)$$

where  $g$  is gravity,  $\rho$  is ocean density,  $c_p$  is specific heat of water,  $S_0$  is surface salinity,  $\alpha$  is the effective thermal expansion coefficient ( $-\rho^{-1} d\rho/dT$ ), and  $\beta$  is the effective haline contraction coefficient ( $\rho^{-1} d\rho/dS$ ).  $Q_0$  has units  $W m^{-2}$ ,  $E$  and  $P$  have units  $m s^{-1}$ , and  $B_0$  has units  $m^2 s^{-3}$ . A negative (i.e. downward) buoyancy flux, due to either surface warming or precipitation, tends to

make the ocean surface more buoyant. Conversely, a positive buoyancy flux, due to either surface cooling or evaporation, tends to make the ocean surface less buoyant. As the water column loses buoyancy, it can become convectively unstable with heavy water lying over lighter water.

Turbulence generated by the ensuing convective overturning can then cause deeper, generally cooler, water to be entrained and mixed into the surface mixed layer (Fig 1). Thus entrainment mixing typically causes the SST to cool and the mixed layer to deepen. Entrainment mixing can also be generated by wind stirring.

Figure 3 shows the climatological evaporation and precipitation fields. Note that in terms of buoyancy, a  $20 \text{ Wm}^{-2}$  heat flux is approximately equivalent to a  $5 \text{ mm day}^{-1}$  rain rate. Thus, in some regions of the world oceans the freshwater flux term in (1) dominates the buoyancy flux, and hence is a major factor in the mixed layer thermodynamics. For example, in the tropical regions, heavy precipitation can result in a surface-trapped freshwater pool that forms a shallower mixed layer within a deeper nearly-isothermal layer. The difference between the shallower mixed layer of uniform density and the deeper isothermal layer is referred to as a salinity-stratified barrier layer. As the name suggests, a barrier layer can effectively limit turbulent mixing of heat between the ocean surface and the deeper thermocline since entrainment mixing of the barrier layer water into the mixed layer results in no heat flux, if the barrier layer water is the same temperature as the mixed layer. In regions with particularly strong freshwater stratification, solar radiation can warm the waters below the mixed layer, causing the temperature stratification to be inverted (cool water above warmer water). In this case, entrainment mixing produces warming rather than cooling within the mixed layer.

In sub-polar latitude, freshwater fluxes can also dominate the surface layer buoyancy

profile. During the winter season, atmospheric cooling of the ocean, and stronger wind mixing leaves the water column isothermal to great depths. Then wintertime ice formation extracts freshwater from the surface layer, leaving a saltier brine that further increases the surface density, decreases the buoyancy, and enhances the deep convection. This process can lead to Deep Water formation as the cold and salty dense water sinks and spreads horizontally, forcing the deep, slow thermohaline circulation. Conversely, in summer when the ice shelf and icebergs melt, freshwater is released, and the density in the surface layer is reduced so that the resultant stable halocline (pycnocline) inhibits the sinking of water.

### *C. Wind forcing*

The influence of the winds on the ocean circulation and mass field cannot be overstated. Wind blowing over the ocean surface causes a tangential stress (“wind stress”) at the interface which acts as a vertical flux of horizontal momentum. Similar to the air-sea fluxes of heat and moisture, this air-sea flux of horizontal momentum,  $\tau_0$ , can be expressed in terms of bulk properties as:

$$\tau_0 = \rho_a C_D S (\mathbf{w} - \mathbf{u})$$

where  $\rho_a$  is the air density,  $C_D$  is the drag coefficient,  $S$  is the wind speed relative to the ocean, and  $(\mathbf{w} - \mathbf{u})$  is the wind vector relative to the ocean surface flow. The units of the surface wind stress are  $\text{N m}^{-2}$ . If the upper ocean has a neutral or stable stratification, then the force imparted by the wind stress will generate a momentum flux that is maximum at the surface and decreases with depth through the water column. Consequently, a vertical shear in the velocity develops in the upper ocean mixed layer. The mechanisms by which the flux of momentum extends below

the interface are not well understood. Some of the wind stress goes into generating ocean surface waves. However, most of the wave momentum later becomes available for generating currents through wave breaking, and wave-wave and wave-current interactions. For example, wave-current interactions associated with Langmuir circulation can set up large coherent vortices which carry momentum to near the base of the mixed layer. As with convective overturning, wind stirring can entrain cooler thermocline water into the mixed layer, producing a colder and deeper mixed layer. Likewise, current shear generated by the winds can cause “Kelvin Helmholtz” shear instabilities that further mix properties at the base of the mixed layer.

Over timescales longer than a pendulum day, the Earth’s spinning tends to cause a rotation of the vertical flux of momentum (see Ekman transport and pumping). From the non-inertial perspective of an observer on the rotating Earth, the tendency to rotate appears as a force, referred to as the Coriolis force. Consequently, the wind forced surface layer transport (‘Ekman transport’) tends to be perpendicular to the wind stress. Because the projection of the Earth’s axis onto the local vertical axis (direction in which gravity acts) changes sign at the equator, the Ekman transport is to the right of the wind stress in the northern hemisphere and to the left of the wind stress in the southern hemisphere. Convergence and divergence of this Ekman transport leads to vertical motion which can deform the thermocline and set the subsurface waters in motion. The steady, large-scale flow driven by the wind stress curl is commonly referred to as the “Sverdrup transport”.

The influence of Ekman upwelling on SST can be seen along the eastern boundary of the ocean basins and along the equator (Fig. 2b). Equatorward winds along the eastern boundaries of the Pacific and Atlantic Oceans cause an offshore-directed Ekman transport. Mass conservation

requires that this water be replaced with upwelled water, water that is generally cooler than the surface waters outside the upwelling zone. Likewise, in the tropics, prevailing easterly trade winds cause poleward Ekman transport. At the equator, this poleward flow is both northward and southward and results in substantial surface divergence and upwelling. As with the eastern boundary, the equatorial upwelling results in relatively cold SSTs (Fig 2b). Because of the geometry of the continents, the thermal equator favors the northern hemisphere and is generally found several degrees of latitude north of the equator.

In the tropics, winds tend to flow from cool SSTs to warm SSTs, where deep atmospheric convection can occur. Thus, surface wind convergence in the intertropical convergence zone (ITCZ) is associated with the thermal equator, north of the equator. The relationship between the SST gradient and winds accounts for an important coupling mechanism in the tropics.

### **III. The Seasonal Cycle**

#### ***A. The North Pacific: A one-dimensional ocean response to wind and buoyancy forcing***

From 1949 through 1981, a ship (“Ocean Station PAPA”) was stationed in the North Pacific at 50°N 145°W with the primary mission of taking routine ocean and atmosphere measurements. The seasonal climatology observed at this site (Figure 4) illustrates classic near-one-dimensional ocean response to wind and buoyancy forcing. A one-dimensional response implies that only the vertical structure of the ocean is changed by the forcing.

During springtime, layers of warmer and lighter water are formed in the upper surface in response to the increasing solar warming. By summer, this buoyancy-induced heating has built a stable, shallow seasonal pycnocline that traps the warm surface waters. In fall, storms are more

frequent and net cooling sets in. By wintertime, the surface layer is mixed by wind stirring and convective overturning. The summer pycnocline is eroded and the mixed layer deepens to the top of the permanent pycnocline.

To first approximation, horizontal advection does not seem to be important in the seasonal heat budget. The progression appears to be consistent with a surface heat budget described by:

$$\partial T / \partial t = Q_o / (\rho c_p H)$$

where  $\partial T / \partial t$  is the local time rate of change of the mixed layer temperature, and  $H$  is the mixed layer depth. Since only vertical processes (e.g. turbulent mixing and surface forcing) affect the depth and temperature of the mixed layer, the heat budget can be considered one-dimensional.

A similar one-dimensional progression occurs in response to the diurnal cycle of buoyancy forcing associated with daytime heating and nighttime cooling. Mixed layer depths can vary from being just a few meters thick during daytime to being several tens of meters thick during nighttime. Daytime and nighttime SST can sometimes differ by over a degree Celsius. However, not all regions of the ocean have such an idealized mixed layer seasonal cycle. Our second example shows a more complicated seasonal cycle in which the tropical atmosphere and ocean are coupled.

### ***B. Coupled ocean-atmosphere variability***

Because there is no Coriolis turning at the equator, water and air flow are particularly susceptible to horizontal convergence and divergence. Small changes in the winds patterns can cause large variations in oceanic upwelling, resulting in significant changes in SST and

consequently in the atmospheric heating patterns. This ocean and atmosphere coupling thus causes initial changes to the system to perpetuate further changes.

At the equator, the sun is overhead twice per year: in March and again in September. Therefore one might expect a semiannual cycle in the mixed layer properties. While this is indeed found in some parts of the equatorial oceans (e.g. in the western equatorial Pacific), in the eastern equatorial Pacific the annual cycle dominates. During the warm season (February-April), the solar equinox causes a maximum in insolation, equatorial SST is warm and the meridional SST gradient is weak. Consequently, the ITCZ is near the equator, and often a double ITCZ is observed that is symmetric about the equator. The weak winds associated with the ITCZ cause a reduction in latent heat loss, wind stirring, and upwelling, all of which lead to further warming of the equatorial SSTs. Thus the warm SST and surface heating are mutually reinforcing.

Beginning in about April-May, SSTs begin to cool in the far eastern equatorial Pacific, perhaps in response to southerly winds associated with the continental monsoon. The cooler SSTs on the equator cause an increased meridional SST gradient that intensifies the southerly winds and the SST cooling in the far eastern Pacific. As the meridional SST gradient increases, the ITCZ begins to migrate northward. Likewise, the cool SST anomaly in the far east sets up a zonal SST gradient along the equator that intensifies the zonal trade winds to the west of the cool anomaly. These enhanced trade winds then produce SST cooling (through increased upwelling, wind stirring and latent heat loss) that spreads westward (Figure 5).

By September, the equatorial cold-tongue is fully formed. Stratus clouds, which tend to form over the very cool SSTs in the tropical Pacific, cause a reduction in solar radiation, despite the equinoxal increase. The large meridional gradient in SST associated with the fully formed

cold-tongue causes the ITCZ to be at its northernmost latitude. After the cold tongue is fully formed, the reduced zonal SST gradient within the cold tongue causes the trade winds to weaken there, leading to reduced SST cooling along the equator. Finally, by February, the increased solar radiation associated with the approaching vernal equinox causes the equatorial SSTs to warm and the cold tongue to disappear, bringing the coupled system back to the warm season conditions.

#### **IV. Conclusion**

Because the ocean mixed layer responds so rapidly to surface generated turbulence through wind and buoyancy forced processes, the surface mixed layer can often be modeled successfully using one-dimensional (vertical processes only) physics. Surface heating and cooling cause the ocean surface to warm and cool; evaporation and precipitation cause the ocean surface to become saltier and fresher. Stabilizing buoyancy forcing, whether from net surface heating or precipitation, stratifies the surface and isolates it from the deeper waters. Whereas wind stirring and destabilizing buoyancy forcing generate surface turbulence that cause the surface properties to mix with deeper water. Eventually, however, one-dimensional models drift away from observations, particularly in regions with strong ocean-atmosphere coupling and oceanic current structures. The effects of horizontal advection are explicitly not included in one-dimensional models. Likewise, vertical advection depends upon horizontal convergences and divergences and therefore is not truly a one-dimensional process. Finally, wind and buoyancy forcing can themselves depend upon the horizontal SST patterns, blurring the distinction between forcing and response.

Although the mixed layer is the principle region of wind and buoyancy forcing, ultimately

the effects are felt throughout the world's oceans. Both the wind-driven motion below the mixed layer and the thermohaline motion in the relatively more quiescent deeper ocean originate through forcing in the surface layer that causes an original adjustment in the field of mass (i.e. density profile). In addition, buoyancy and wind-forcing in the upper ocean define the property characteristics for all the individual major water masses found in the world oceans. On a global scale, there is surprisingly little mixing between water masses once they acquire the characteristic properties at their formation region and are vertically subducted or convected from the active surface layer. As these subducted water masses circulate through the global oceans and later outcrop, they can contain the memory of their origins at the surface through their water mass properties and thus can potentially provide decadal and centennial modes of variability in the ocean-atmosphere climate system.

## **FURTHER READING**

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## FIGURE LIST

Figure 1. Wind and buoyancy forces acting on the upper ocean mixed layer.

Figure 2. Mean climatologies of (a) net surface heat flux in units  $\text{Wm}^{-2}$  and, (b) sea surface temperature in units degrees Celsius, and surface winds in units  $\text{ms}^{-1}$ . Climatologies provided by da Silva et al. (1994). A positive net surface heat flux acts to warm the ocean.

Figure 3. Mean climatologies of (a) evaporation, and (b) precipitation from da Silva et al. (1994). Both have units  $\text{mm day}^{-1}$ .

Figure 4. Seasonal climatologies at the ocean weather station PAPA in the north Pacific. (top panel) Wind speed, (middle panel) net surface heat flux, and (bottom panel) upper ocean temperature. The thick line represents the base of the ocean mixed layer defined as the depth where the climatological temperature is  $0.5^{\circ}\text{C}$  cooler than the surface temperature. Wind speed and net surface heat flux climatologies are from da Silva et al. (1994).

Figure 5. Tropical Pacific sea surface temperature and wind for the climatological (a) February-March-April, (b) May-June-July, (c) August-September-October, and (d) November-December-January. Winds are from da Silva et al. (1994). SSTs are from Reynolds and Smith (1994).

**Keywords:** ocean mixed layer, wind forcing, buoyancy, air-sea interactions, mixing processes, one dimensional models, coupled models, wind-driven circulation, thermohaline circulation, convection, seasonal cycle, heat budget, freshwater budget.

**Cross-reference with:** one dimensional models, surface wind driven circulation, thermohaline circulation, water types and water masses, Pacific equatorial currents, Ekman transport and pumping, heat and freshwater budgets, mixing processes, penetrating shortwave radiation, responses to strong forcing events, time and space variability, vertical structure.